Importance of airglow and auroral emissions as tracers of Venus' upper atmosphere dynamics and evolution

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Importance of airglow and auroral emissions as tracers of Venus' upper atmosphere dynamics and evolution. E.M. Royer¹, C. Gray², A. Brecht³, D. Gorinov⁴, and S. Bougher⁵, ¹Planetary Science Institute (PSI), 1700 E Fort Lowell Rd, Suite 106, Tucson, AZ 85719, emilieroer@psi.edu ²New Mexico State University, 1780 E University Ave, Las Cruces, NM 88003, candaceg@nmsu.edu, ³NASA Ames, ⁴Space Research Institute, ⁵University of Michigan

Summary: The goal of this white paper is to advocate for a thorough monitoring of Venus' upper atmosphere, through future space missions. Venus is a natural laboratory, which enables the study of solar wind interactions with planetary bodies without intrinsic magnetic field. Beyond the basic knowledge of the composition, structure, and dynamics of an atmosphere, aeronomic emissions provide further elements toward answering fundamental questions related to dynamics, energy transport, escape processes, solar wind/magnetospheric interactions with the upper atmospheres and the history of water at Venus. This paper includes an overview of the current state of knowledge on the upper atmosphere circulation regimes, identifies knowledge gaps that need to be addressed, and emphasizes strong arguments on why we need to go back to Venus. Additionally, we highlight which upper atmosphere observations are necessary to improve Global Climate Models (GCM) and our understanding of atmospheric physical processes at play.

Background and Motivation: The upper atmosphere of Venus is the location of many unveiling physical and chemical processes driving the atmospheric dynamics and transport, but also a place where many puzzling questions on the origin and evolution of the current Venus' atmosphere remain to be answered. Why Venus? As previously mentioned, it is a natural laboratory for studying unmagnetized planets, and it is a slow rotator. These are unique traits for a terrestrial planet in our solar system but might be more common as we continue to discover more exo-planets. The most enticing part about Venus, is its close proximity to Earth and therefore “easier” to study. What can be learned from Venus can help us understand other terrestrial planets such as our own home, Earth.

Figure 1. Circulation regimes in the Venusian atmosphere. On this North Pole view of Venus, the dayside is represented by the white inner half-circle. At altitudes from 0 to 70 km, a retrograde super-rotating zonal (RSZ) flow takes place. Above 120 km of altitude, up to the exobase at 220 km of altitude, a sub-solar/anti-solar circulation and the RSZ flow co-exist. A 50 km wide transition zone is located between 70 to ~120km of altitude. In this zone, the lower retrograde super-rotating zonal flow, the dominating sub-solar/anti-solar circulation and the upper retrograde super-rotating zonal flow are inter-connected. The transition zone is represented by the squared line patterns to emphasis how little is currently understood regarding the dynamics of this region. Nightglow and auroral phenomenon, represented in green, are shown on the nightside. Adapted from [4] & [5].

The drivers and interactions within Venus' global zonal wind system is shrouded with mystery. Below 70 km of altitude, i.e. below the cloud deck, Venus possesses a stable retrograde super-rotating zonal flow, dominating the atmospheric circulation. At altitudes between ~70 and ~120km, this retrograde super-rotating zonal flow greatly weakens and the dominant circulation transitions to the sub-solar/anti-solar circulation, as sketched in Figure 1. This 50 km wide region is known as the Transition zone: at about 70km of altitude the lower and stable retrograde super-rotating zonal flow transitions to a sub-solar/anti-solar circulation; at about 120km, the sub-solar/anti-solar circulation merges with, this time, a variable upper retrograde super-rotating zonal flow. The large variability of the retrograde super-rotating zonal winds between ~80 and 110 km is still the subject of considerable debate [1][2][3][4][27][28].

A possible explanation for increased zonal wind velocity at higher altitudes would be that night side westward moving O^+ ions, moving in the super-rotation direction, exchange momentum with the ambient neutral gas down to the lower thermosphere [14]. Other investigators have attributed the wind variability in the transition zone to the changing nature of gravity wave breaking in this region [1][15][16][17]. Alternatively, upward propagating tides and planetary scale waves may serve to significantly modify the density and wind structure of the Venus upper atmosphere, analogous to that which has been observed at Mars [18][19]. Nevertheless, the processes responsible for maintaining and driving variations in the sub-solar/anti-solar and the retrograde super-rotating zonal winds in the Venusian upper atmosphere are still not well understood or quantified [1]. Furthermore, **the lack of consistent and long-term measurements and observations of the transition region prohibits a clear understanding of the processes driving the atmospheric dynamics and transport at play in this region of the atmosphere.**

Because of its proximity to the Sun, the space environment at Venus is largely controlled by solar activity. Thus, Venus' upper atmosphere is strongly influenced by external factors, such as the solar wind and solar particles. Due to the lack of an intrinsic magnetic field, Venus has a different interaction with the space environment compared to Earth and Mars. Example of solar activity includes stream interaction regions (SIRs), solar flares, and coronal mass ejections (CMEs). SIRs are dense solar wind streams that are generated when a fast ($> 300 \text{ ms}^{-1}$), low density solar wind stream interacts with a slow ($< 300 \text{ ms}^{-1}$), high density stream, creating a denser solar wind stream [20]. Solar flares are outbursts of electromagnetic radiation, particularly in the radio, EUV, and X-ray bands. Charged particles and solar energetic particles (SEPs, charged particles with relativistic high energy ranging between keV to MeV) can also be associated with solar flares but are not observed for all flares [6]. CMEs are ejections of disconnected magnetic fields and plasma produced above the Sun's photosphere near the corona. CMEs move nearly radially away from the Sun traveling at speeds of $500 - 2000 \text{ km.s}^{-1}$. All these **solar events interact with the neutral upper atmosphere (temperature, winds, and composition) which then can create an ionosphere and alter the structure and behavior of the upper atmosphere.**

Solar wind interactions lead toward atmospheric loss at Venus. Energetic particle precipitating into Venus atmosphere at high speed have the potential to strip some of Venus minor and major constituents, namely H and O. The terrestrial planets, Venus, Earth and Mars, are believed to be borne with primary atmospheres of similar composition, which then evolved in the secondary current atmosphere that we know. Among them, Venus is extremely dry compared to Earth's atmosphere, with a D/H ratio of 100 times that of Earth's, indicating of an important loss of water through its history. **Monitoring the upper atmosphere of Venus and its interaction with the solar wind, will provide critical information on atmospheric escape and the non-thermal escape processes at play at Venus.**

Zonal flows, interactions, and variations in the upper atmosphere are known based on the limited spacecraft and ground-based observations that currently exist. There are key features, such as airglow and auroral emissions, that can be observed and used to help qualify and quantify the various interactions between Venus' upper neutral atmosphere, its ionosphere, and the incoming solar wind.

Observables: Airglow and aurora are emissions in response to neutral atmosphere dynamics, chemistry, and interactions with the space environment. They provide information about chemical reaction rates, transport, thermal structure, winds, and overall dynamics of the upper atmosphere.

Airglow: The two most observed airglow features at Venus are Nitric Oxide (NO) and O₂ emissions on the nightside. They provide an excellent example of what can be gleaned from these types of observables. The NO and O₂ nightglow (airglow on the nightside) peak at about 110 km and 95 km of altitude, respectively. They present discrepancies in their brightness peak location, which are not well-explained by current global climate models. Both nightglow features originate from the radiative recombination of atoms created on the dayside by photodissociation and traveling to the night side, where they recombine in either NO or O₂, emitting in the ultraviolet or the infrared, respectively. If the sub-solar/anti-solar circulation were the sole driving factor of the circulation, we would expect both nightglows' peaks in brightness to be distributed around the anti-solar point, i.e. midnight local time. When averaged over long-term periods, this behavior is generally observed for the O₂ nightglow (Figure 2a). Nevertheless, the NO peak is observed to be shifted by 2 hours local time toward the morning terminator, as displayed in Figure 2b. Both aeronomic emissions reveal abrupt changes of atmospheric dynamics within a short span of altitude (15 km). Additionally, another intriguing property of these nightglow features is their highly variable nature when observed on a day to day basis, which becomes organized (nightglow peaking around the anti-solar point) when observed over longer time scales of several years [9][10]. This last point reinforces how little we currently understand of the dynamical processes and transport at play in the transition region.

Figure 2. Maps of the statistical distribution of the O₂ (a) and NO (b) nightglow intensities. The disk is centered on the anti-solar point. The difference between the bright spot location of O₂ and NO emission suggests two different dominant wind regimes at 95 and 110 km [8].

Observations/Instruments Needed:

Venus Express observed the O₂ and NO nightglow from 2006 to 2014. However, due the polar orbit of the spacecraft, spatial and temporal gaps in coverage exist. To answer remaining questions regarding

the variability of the retrograde super-rotating zonal flow in the transition zone, both O₂ and NO nightglow needs to be simultaneously monitored by an infrared and an ultraviolet spectrometer, respectively. Ideally, disk-integrated simultaneous observations of both nightglows would allow for the vertical wind coverage of the Venusian atmosphere at altitude from 80 to 120km. An equatorial orbit would provide best results in terms of temporal, day by day, coverage of the nightglow. More specifically, a sun-synchronous configuration, allowing for a systematic coverage of the midnight local time area of both nightglows, would produce best returns for assessing the vertical structure of the transition zone. Additionally, to avoid the data gaps similar to those from Venus Express, and to fully understand the oxygen and NO nightglow behavior, a thorough local time and latitude coverage is needed as well.

Aurora: Though Venus lacks a magnetic field, it exhibits diffuse auroral emission during times of increased solar activity. This solar activity includes stream interaction regions (SIRs), solar flares, and coronal mass ejections (CMEs), which are known to generate auroral emission in planetary atmospheres. Auroral emission at Venus have been detected for OI (3S - 3P) and (5S - 3P) intensities at 130.4 and 135.6 nm respectively, and OI (1S - 1D) emission at 557.7 nm (oxygen green line), as shown in Figure 3. While the oxygen green line is exhibited as auroral and nightglow emission on Earth, it is only observed as auroral emission on Venus. These emissions probe different parts of the upper atmosphere and can provide information about energy propagation through the Venusian atmosphere.

Figure 3. Sequence of Pioneer Venus Orbiter UV spectrometer images of the nightside of Venus showing auroral variations observed in the 130.4nm line of atomic oxygen. The black crescent represents the visible section of the sunlit hemisphere. Phillips et al. (1986) observed an increase in the OI (3S - 3P) and (5S - 3P) intensities at 130.4 and 135.6 nm respectively, during a solar storm. While typical intensities were found to be 10 R, outbursts exceeded 100 R. These outbursts coinciding with elevated energetic particle fluxes measured by the Pioneer Venus Orbiter gamma-ray burst detector as well as the passage of a magnetic shock, indicative of a CME [21].

The OI (1S - 1D) emission at 557.7 nm (oxygen green line) is consistently detected after particles storms such as CMEs and SIRs [22] [23]. Like the OI UV auroral lines, emission is detected immediately following solar storm impacts, indicating that emission is controlled by particles precipitating directly on the nightside. Furthermore, density changes in the nightside ionospheric layers are also observed during CMEs impacts. The lower ionospheric layer (V1 layer, located near 125 km) is seen to increase more than an order of magnitude during large CMEs impacts while the V2 layer (near 150 km) shows little change or even a decrease in density [23]. The coincident auroral emission and low ionospheric density increases suggest that high energy particles are penetrating deep into the Venusian nightside, leading to green line emission without the longer lifetime oxygen red line counterpart observed in the Earth's aurora (Figure 4).

It is interesting to note that both the NO nightglow and OI 130.4nm aurora exhibit similar spatial offsets (no full disk spectral images exist for oxygen green line emission), with peak emission shifted towards the dawn terminator of the nightside, indicating the return of retrograde super-rotating zonal (RSZ) flow. It has been suggested that the return of the RSZ at high altitudes may be due to atmospheric interactions with the solar wind. Simulations of the solar wind interaction with Venus' atmosphere performed by the hybrid particle code HALFSHEL and the Venus Thermosphere General Circulation Model (VTGCM) are demonstrating the importance of energetics and the solar wind on the dynamics of the Venusian upper atmosphere. It has been found that changes to the neutral wind dynamics modify the solar wind interaction and its electromagnetic coupling to the neutral atmosphere [26]. By introducing the super-rotating winds observed on Venus (vs. modeling with no super rotation), Brecht et al. (2018) found that solar wind particles and electromagnetic fields were asymmetrically adding energy to the upper atmosphere [25]. Recent VTGCM simulations show that O+ particle heating results in elevated neutral temperatures (patchy warming up to +25-40K) over 160 to 200 km on the Venus dayside. Nightside warming is even more variable. Corresponding peak momentum deposition should occur over the same altitude range as the energy deposition (~135-160 km). Thus, this asymmetric energy deposition supports the hypothesis that the RSZ winds are driven by the plasma interaction [26]. The exact role of this ion-neutral drag, and its contribution to the super-rotating winds of Venus, are still being investigated.

Figure 4. Electron density of the V1 and V2 nightside ionospheric layers on the nightside (SZA > 115) with one sigma variation marked as dotted lines for: a) Average of profiles before CME impacts b) average of profiles after CME impacts [24].

Observations/Instruments Needed:

Given the full disk view that is needed to discern spatial variation in the Venusian nightglow and aurora, an orbiter is an ideal platform to understand upper atmosphere dynamics and its connection with the solar wind. A circular orbit that tracks the motion of the upper atmosphere will allow for stationary monitoring of the atmosphere. Additionally, a spacecraft on an elliptical orbit will allow for the sampling of the solar wind inside and outside the bow shock of Venus. Desired instruments for atmospheric monitoring are hyperspectral imaging with UV, VIS, and IR spectrometers having sensitivity to nightside emissions. Desired instruments to monitor the solar wind, in order to better understand how the solar wind interacts with the upper atmosphere, include a suite of magnetometer, electron and ion spectrometers, and SEP detector.

Escape Processes: Understanding where Venus' water has gone is important to understand in the context of the evolution of the three major terrestrial planets in our solar system (Venus, Earth, Mars). This type of investigation is currently going on at Mars and the Mars Atmosphere and Volatile Evolution (MAVEN) mission has been proven invaluable in understanding the mechanisms of atmospheric escape at Mars. Given the success of MAVEN and the phenomenal scientific return of the mission, it is now time critical to perform an identical study at Venus, under similar solar cycle conditions, to improve our understanding of CO₂ dominated atmospheres and decipher how the path of Venus deviated from the one of Mars or Earth.

Observations/Instruments Needed:

A mission of same caliber as MAVEN, comprising a suite of in-situ ions and electron analyzer and a multi-wavelengths (UV, Vis and IR) remote-sensing platform for airglow studies, happening within the next decade, will provide the best return for a cross-comparison of CO₂ dominated atmosphere at Mars and Venus.

Conclusion: In this white paper, we advocate for a thorough spatially and temporally complete monitoring of the Venus upper atmosphere in the next decade to accomplish three goals:

- 1 – Improving our understanding of atmospheric dynamics and transport in the transition zone
- 2 – Studying the mechanisms of interactions between an unmagnetized body such as Venus and the solar wind
- 3 – Acquiring long term and spatially adequate measurements of Venus' upper atmosphere to provide insight into Venus' atmospheric dynamics and evolution of water content

Venus' various nightglow emission features occur in the transition zone, a 50 km deep poorly understood region of the Venusian atmosphere, at the interface of two major circulation regimes. Studying airglow is one of the most feasible and accessible ways to increase our understanding of the atmospheric circulation in the transition zone, as airglow emissions act as tracers of the dynamics of the descending branch of the sub-solar/anti-solar circulation and their departure from expected patterns bears the imprint of the superimposed retrograde super-rotating zonal flow. Acquiring better data on the Venusian upper atmosphere will greatly improve and more realistically constraint Venusian global climate models. More information on this subject is given in a white paper led by A. Brecht.

Venus, as an unmagnetized body, is also a natural laboratory to study the effect of magnetic field on planetary evolution. The scientific community would greatly benefit from the pursuit of a mission like MAVEN at Venus (VAVEN). MAVEN brought new and incredible insights into the atmospheric escape processes at Mars. Doing the same at Venus would bring critical information on the history of water at Venus and how H and O atoms (i.e. water H₂O) currently escape the atmosphere. A suite of instruments remotely monitoring the upper atmosphere (UV, Vis and IR spectrometers) and measuring in-situ characteristics of the plasma, solar wind and magnetic environment is becoming a necessity to further our understanding of terrestrial atmospheres' evolution. Previous missions such as Venus Express and the current Akatsuki missions provide a wealth of information on the lower/middle atmosphere but to date, no spacecraft missions has been dedicated to the transition regions from 70-120 km and above.

Furthermore, as mentioned in introduction, the dedication of the exploration of Venus' upper atmosphere has potential implications for cross-disciplinary investigations, such as climate change and greenhouse effect studies at Earth, magnetospheric studies through the solar system and exoplanetary studies of Exo-Venuses, i.e. planets orbiting very close to their star. This white paper is thus of interest

to scientific communities at large working on planetary atmospheres, exoplanets/exo-Venus, along with global circulation modelers.

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